

Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings

Alexander Passer · Helmuth Kreiner · Peter Maydl

Received: 15 March 2011 / Accepted: 12 April 2012 / Published online: 8 May 2012
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Abstract

Purpose Sustainability assessments of buildings using the life cycle approach have become more and more common. This includes the assessment of the environmental performance of buildings. However, the influence of the construction products used for the fabric, the finishing, and the technical building equipment of buildings has hardly been described in literature. For this reason, we evaluated the influence of the technical building equipment and its impact on the environment for different residential buildings.

Materials and methods Five residential buildings were evaluated by applying the methodology of life cycle assessment (LCA) (ISO14040) expressed using quantitative assessment categories according to prEN15978.

Results and discussion Results show that the optimization of energy performance has already reached a high level in Austria, so that the overall potential for possible improvements is quite low. Especially in low-energy and passive-house-standard residential buildings, the limits for energy optimization in the use phase have mostly been achieved. In contrast to this, the integrated LCA (iLCA) findings attribute a high optimization potential to the construction products used for the technical building equipment as well as to the building fabric and finishing. Additionally, the passive house shows the lowest contribution of the technical building equipment on the overall LCA results.

Conclusions The iLCA findings suggest that it is recommended to include the technical building equipment for

future assessments of the environmental performance of buildings. It is also suggested to use a broad number of environmental indicators for building LCA.

Keywords Embodied and operational energy · Environmental performance of residential buildings · Integrated LCA (iLCA) · Technical building equipment

1 Introduction

With the publication of the Brundtland Report in 1985 and the Rio Declaration in 1992 (Schubert and Láng 2005; Klöpffer 2003; WECD 1987), sustainable development has become a well-known global paradigm. Due to the fact that the construction sector plays a key role in the consumption of energy and resources as well as in solid waste accumulation (e.g., Wallbaum and Meins 2009; Maydl 2006; Maydl 2004), it is important to quantify the environmental performance of buildings in order to communicate their potential environmental impacts and aspects as well as their influence on sustainable development.

To apply the sustainability concept to the construction sector, quantifiable measurement methods are needed. Methods for the assessment of the environmental performance of buildings have been developed since the early 1990s. The *International Standardization Organization* (ISO)¹ prepared the first standards that intended to address specific issues and aspects of sustainability relevant to

A. Passer (✉) · H. Kreiner · P. Maydl
Institute of Technology and Testing of Building Materials, Graz
University of Technology,
Inffeldgasse 24,
8010 Graz, Austria
e-mail: Alexander.Passer@TUGraz.at

¹ Technical Committee ISO/TC 59, Building construction, Subcommittee SC 17, Sustainability in building construction (International Organization for Standardization 2008a; International Organization for Standardization 2010a; International Organization for Standardization 2007; International Organization for Standardization 2010b; and ISO21932)

building and civil engineering of construction works. Already these standards are founded on the Life Cycle Assessment methodology (LCA) in ISO 14040 (International Organization for Standardization 2006a).

On the basis of the ISO work, the European Committee for Standardization² is working on a set of standards to harmonize the methodology for a sustainability assessment of buildings using the life cycle approach. According to FprEN 15643–2 (European Committee for Standardization 2010b) and FprEN 15978 (European Committee for Standardization 2011), the assessment of the environmental performance of buildings is based on LCA expressed with quantitative categories.

Apart from this standardization work, a growing number of tools and building certification systems, such as LEED,³ BREEAM,⁴ DGNB,⁵ ÖGNI⁶, and TQB⁷ have appeared on the market to endorse green and sustainable buildings (Ortiz et al. 2009; Passer et al. 2009a,b; Gertis et al. 2008; Graubner and Lützkendorf 2007; Mateus and Bragança 2011). Recently, an increasing demand for such labels has been observed (Henzelmann et al. 2010). In certification systems for sustainable building, aspects of sustainability (economic, social, and environmental as well as functional and technical performance) are considered very differently (Passer et al. 2009a,b; Wallhagen and Glaumann 2011)—especially as regarding the assessment of the environmental performance. As several building certification systems involve the assessment of the environmental performance of buildings with the use of LCA, this methodology is becoming more and more important (Humbert et al. 2007; Ortiz et al. 2009; Optis and Wild 2010; Passer et al. 2011).

Considering the fact that the optimization of energy performance (European Parliament and Council of the European Union 2010) has become one of the primary objectives in Europe,⁸ it will henceforth be appropriate to concentrate increasingly on the construction products used for the buildings. Otherwise, environmental impacts might shift to life cycle stages which are not assessed at the moment, i.e., percentage of embodied energy included in different LCA studies (Blengini and Di Carlo 2010; Optis and Wild 2010; Passer 2010). This correlates with the suspicion voiced in previous studies (Humbert et al. 2007) that most of the buildings which

are, e.g., rated LEED platinum have an overall reduction of impacts of less than 15 % compared with the one of the same building without certification. Furthermore, this underlines the need for improving certification systems in accordance with the CEN/TC 350 standards.

Looking at the LCA in the building sector, there are mainly two different research approaches. The first deals with LCA of buildings (i.e., its energy performance, e.g., Optis and Wild 2010; and the building materials, e.g., Gustavsson and Sathre 2006; Nebel et al. 2006); the second one investigates technical systems and/or technical building equipment (Heikkilä 2004; Prek 2004; Ardente et al. 2005; Kannan et al. 2006; Shah et al. 2008; Blom et al. 2010; Dodoo et al. 2011). An overview can be found in Ortiz et al. (2009) and Optis and Wild (2010), where the LCA methodology and tools employed in the built environment are presented as well as the differences between the LCA of building materials and component combinations versus the LCA of the full building life cycle. Studies, which investigate the LCA of buildings and technical building equipment in the same study, are rare (e.g., Blom et al. 2010; Blengini and Di Carlo 2010). The influence of the technical building equipment in terms of an integrated LCA (iLCA)⁹ perspective could not be found in literature.

The quantification of the environmental performance of buildings by the use of LCA is a work-intensive exercise as, to date, no appropriate tool is available which considers simultaneously the installed construction products and the building operation (Forsberg and von Malmborg 2004; Haapio and Viitaniemi 2008; Ortiz et al. 2009; Bribian et al. 2009; Kellenberger and Althaus 2009; Blengini and Di Carlo 2010). On the one hand, a complete quantification of the building—Life Cycle Inventory (LCI)—requires huge efforts because the combined knowledge of the net amount of construction products is needed. Products have to be classified based on the bill of quantities and detailed specification of each contract items, as well as on their applicability and densities. In today's practice, this information is not very often provided in a sufficient way. On the other hand, the calculation of the environmental indicators (Life Cycle Impact Assessment (LCIA)) demands specific knowledge of life cycle inventory datasets, in particular, how these are composed and what is included, i.e., the system boundary and allocation rules are crucial. This kind of information is provided, for example, in the *ecoinvent* reports (Frischknecht et al. 2007; Weidema et al. 2007). There is, however, still a considerable lack of product specific data for construction products (i.e., Environmental Product Declarations (EPDs)).

² Technical Committee CEN/TC 350 Sustainability of construction works (FprEN15643-1, FprEN15643-2, FprEN15804 and FprEN15978)

³ The Leadership in Energy and Environmental Design (LEED), Green Building Rating System, <http://www.usgbc.org/>

⁴ BRE Environmental Assessment Method (BREEAM) for Buildings Around The World, <http://www.breem.org>

⁵ Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)—The German Sustainable Building Council, <http://www.dgnb.de/>

⁶ Österreichische Gesellschaft für Nachhaltige Immobilienwirtschaft (ÖGNI), Austrian Sustainable Building Council, <http://www.ogni.at/>

⁷ Total Quality Building (TQB), Österreichische Gesellschaft für Nachhaltiges Bauen (ÖGNB), <https://www.oegnb.net/tqb.htm>

⁸ Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)

⁹ The meaning of integrated LCA (iLCA) is synonymous for the attempt in this work to consider the entire building life cycle and all construction products used, especially the consideration of the technical building equipment.

Furthermore, comparisons of different LCA studies have shown that a minimum of documentation has to be supplied (Optis and Wild 2010). If not, provided results remain irreproducible and incomparable.

A detailed description will be available in the near future in the FprEN 15978—sustainability of construction works—assessment of environmental performance of buildings—calculation method.

So far, the construction products for the technical building equipment have hardly been considered in building LCA. The aim of the present work is to close this gap and to provide an assessment of the environmental performance of buildings with the focus on identifying the priorities for the assessment and evaluating the influence of technical building equipment using the LCA method. Therefore, an iLCA of buildings is necessary to quantify the influence of construction products used for technical building equipment as compared with construction products used for the building fabric and finishing.

2 Methods

In order to identify the main influences of the different types of construction products used for fabric, finishing, and technical building equipment (i.e., technical installation) of buildings on their environmental performance, a comprehensive analysis of five different residential buildings was carried out over their building life cycle using the LCA-method. The influence of the construction products is being compared over individual life cycle stages in relation to the building operation. Only this integrated approach allows for correctly quantifying the effective contribution of the technical building equipment.

2.1 Methods for assessment of environmental performance of buildings

This work was undertaken according to the European Standards (European Committee for Standardization 2010a) written by CEN/TC 350 that provide a system for the sustainability assessment of buildings using a life cycle approach. In this concept, the sustainability performance incorporates the environmental, social, and economic performances as well as the technical and functional ones, and they are all intrinsically related to each other. The assessment quantifies impacts and aspects using quantitative and qualitative indicators. The purpose of this series of standards is to enable comparability of results of assessments without value judgments or setting benchmarks or levels of performance. The assessment of the environmental performance of buildings is based on the methodology of LCA (International Organization for Standardization 2006b) expressed using quantitative assessment categories (prEN15643-2 and FprEN15978).

In contrast to the above-mentioned approach, our work only focuses on the quantification of the assessment of the environmental performance of buildings. Thus, trying to quantify only parts of the sustainability performance in general does not seem to be sufficient, and a more integrated LCA approach was adopted.

Figure 1 displays the main steps in the process of assessing the environmental performance according to the FprEN 15978 and gives some examples for required definitions. The scope of the various assessment steps needs to be adjusted to the goal of the assessment. In the various steps, step number 4—“quantification of the building”—similar to the LCI in ISO 14040, takes a major role, since the quantification of the environmental performance can be accomplished on this basis.

2.2 Key parameters

For the assessment, the following key parameters, shown in Table 1, were defined. For the reference study period,

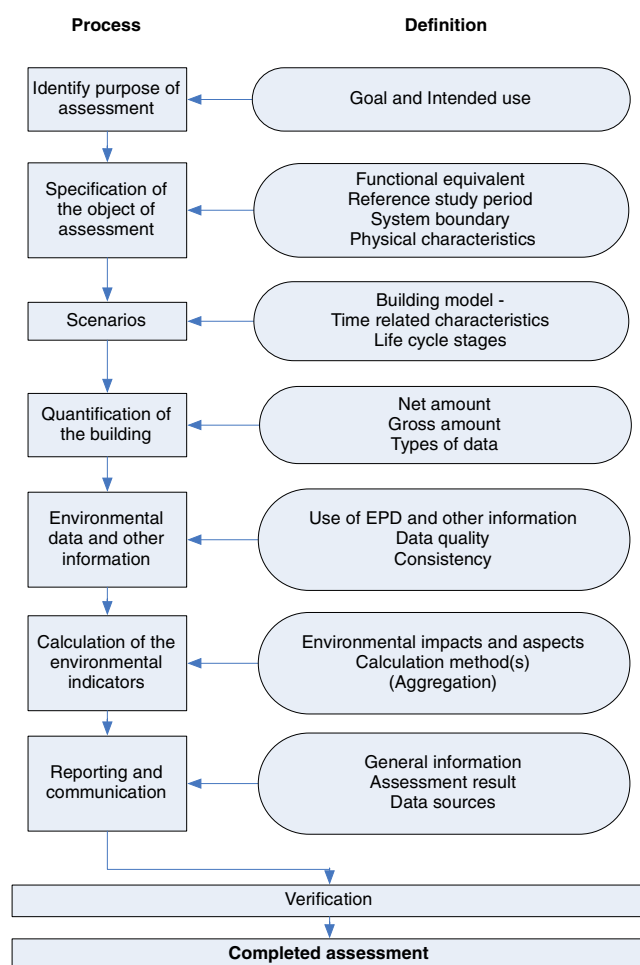


Fig. 1 Main steps within the environmental assessment-workflow according to FprEN 15978

Table 1 Key assessment parameters

Goal	Complete LCA
Scope	Five residential buildings building life cycle entire building products
Reference study period (T_{ref})	50 years
Quantification of the operational energy	According to ÖNORM H 5055
Functional unit	Square meter net floor area (m^2 NFA)
Environmental data	<i>ecoinvent</i> 2.1
Methods	CML 2001, cumulative energy demand
Indicators	AP, EP, GWP, ODP, POCP, CEDr, CEDnr

50 years was assumed. The functional unit used is square meter net floor area (m^2 NFA). A more detailed description will be given later (“Sections 2.3–2.5”).

2.3 Objects of investigation

Five residential buildings were analyzed. Table 2 gives a short overview of the different buildings. More in-depth information about the buildings is given in Passer (2010). The five buildings represent a range of different energy and construction concepts including passive-house to low-energy standard¹⁰ as well as solid construction and timber construction. The sizes of the buildings vary from 683 m^2 to 1,351 m^2 net floor area. The surface/volume ratio ranges for all buildings within the range from 0.50 to 0.58. Heating and hot water are provided via a gas and an air-to-air heat pump (passive house) system, respectively. In two projects, a combined solar heating system was installed. The heating system in building 1 consists of an air-to-air heat pump with the heat being largely distributed via spiral seam ducts used for the ventilation system. In this way, we tried to cover a wide range of buildings with different energy standards and technical building equipments.

In Table 3, the main characteristics in the use phase are shown. Looking at the numbers in the table, it has to be taken into account that these numbers are per square meter net floor area (NFA).

The household electricity demand was taken from statistics in Austria and include the electricity demand for lighting, cooking, and all other kind of services, e.g., computer, TV (Statistik Austria 2010). The calculated demand was based on the number of people living in each household (flat) and divided by the net floor area. The electricity demand of the five buildings varies to some extent as they have different types of flats (people per square meter).

¹⁰ The classification of energy standards is regulated in the Austrian Standard for Energy certificate for buildings (Austrian Standards Institute 2008)

2.4 Inventory analysis

For the LCI based on the bill of quantities for each building, *ecoinvent*¹¹ database v2.1 (Frischknecht et al. 2007, Althaus et al. 2005) was chosen. This database contains industrial life cycle inventory data, for, e.g., energy supply, resource extraction, material supply, metals, waste management services, and transport services.

The life cycle inventory was organized in a matrix. This allowed us to analyze the results for different life cycle stages of a building as well as for the environmental indicators specific to the construction products and specific to the building operation (use stage). Figure 2 shows the organization of the life cycle inventory and inventoried classes. The building life cycle is therefore divided into the before-use, the use, and the end-of-life stage as well as into impacts and aspects specific to the building and specific to operation.

The boundary conditions of the system determine the processes that are taken into account and are divided into time-related and space-related system boundaries. The time-related boundary covers the before-use stage, the use stage, and the end-of-life stage. The space-related system boundary concerns the building. This includes all upstream and downstream processes needed to establish and to maintain the functions of the building, ranging from the acquisition of raw materials to the end-of-life stage.

2.4.1 Before-use stage

The before-use stage covers cradle-to-gate processes for construction products (materials/components) and services used for the construction of the building. The LCI matrix is based on the cost–structure classification of the Austrian Standard ÖNORM B-1801-1 (*Kosten im Hoch- und Tiefbau-Kostengliederung*) (Austrian Standards Institute 2009) in which the construction-work sections are split into building fabric, technical building equipment (i.e., technical installation), and finishing. Table 4 shows selected construction-work sections according to the classification. The complete lists of construction work sections according to ÖNORM B-1801-1 includes more than 50 different sections, and a complete representation is beyond the scope of a journal article. Therefore, Table 4 represents only the most important construction-works. The complete table is published in Passer (2010).

During the modeling of the life cycle inventory for the five buildings, approximately 2,800 contract items (with their related construction products) were investigated for the three different groups, fabric, technical building equipment, and finishing. In a second step, the items were

¹¹ The *ecoinvent* Centre, a competence center of ETHZ, EPFL, PSI, Empa, and ART, Switzerland

Table 2 Main parameters of the five assessed buildings

Characteristics of buildings	1	2	3	4	5
Construction method	Solid construction	Timber construction	Timber construction	Solid construction	Solid construction
Energy-standard	Passive house	Low energy	Low energy	Low energy	Low energy
Gross floor area (m ²)	1,980	1,609	1,381	1,150	970
Net floor area (m ²)	1,351	1,341	1,094	901	683
Net/gross floor (-)	0.68	0.83	0.79	0.78	0.7
Surface/Volume (m ⁻¹)	0.5	0.58	0.55	0.55	0.55
Interior walls	Brick/dry construction (gypsum)	Dry construction (gypsum)	Timber/dry construction (gypsum)	Brick	Dry construction (gypsum)
Thermal insulation	EPS (30 cm)	Mineral wool (12 cm)	EPS/mineral wool (12 cm)	EPS (14 cm)	EPS (12 cm)
Roofing	PVC	Zinc-coated sheet	Zinc-coated sheet	Concrete roofing tile	Concrete roofing tile
Window frame	Plastic	Timber	Plastic	Plastic	Plastic
Heating system	Air-to-air heat pump	Gas	Gas	Gas	Gas
Solar heating	No	No	No	50 m ²	50 m ²
Ventilation	Yes	No	No	No	No

Table 3 Annual final operation energy use (main parameters of the five assessed buildings in the use phase)

Building	1	2	3	4	5
Final energy for house hold electricity (kWh/m ² a)	56.2	61.3	58.8	57.5	62.7
Final energy demand for heating and hot water (kWh/m ² a)	53.4	102.6	93.0	71.8	87.8
Freshwater demand (m ³ /m ² a)	1.5	1.7	1.6	1.6	1.7
Wastewater demand (m ³ /m ² a)	1.5	1.7	1.6	1.6	1.7

analyzed for their LCA relevance, which means that construction work without an influence on LCA, e.g., additional charge for special products or work, was ignored. Ultimately, the LCI-model for the five buildings consisted of approximately 1,700 contract items, which contained about 200 different construction products.

For the LCI of the technical building equipment, the materials for electrical installation, heating, solar heating system, sanitary, and ventilation were taken into account. All technical building equipment materials were analyzed in detail, which means that we included for, e.g., the ventilation the following materials: the central unit, recuperator, control and wiring, the decentralized unit, air filters, spiral-seam ducts, flexible ducts, elbows, connection pieces, ground heat exchanger, silencers, supply air inlets, insulation materials such as, e.g., rockwool and tube insulation.

2.4.2 Use stage

The use stage spans the period from the completion of the construction works to the point when the building reaches its end of life. The system boundary in the use stage includes the use of construction products (maintenance/replacement) and services for operating the building (see Fig. 2).

For all construction products (components/materials) that may be replaced, the estimated service life (ESL) was defined in accordance with ISO 15686 parts 1 and 8 (International Organization for Standardization 2000; International Organization for Standardization 2008b). The number of replacement rates for all specific construction products used in the buildings was calculated according FprEN 15978. Their estimated service life was taken assuming the values by the ESL-Catalogue in Austria (SV 2006). The values given within the ESL are estimates obtained by expert opinions and experience. These values correlate with values in Blom et al. (2010) in the case of the technical building equipment.

2.4.3 End-of-life stage

The end-of-life stage of a building begins after the use stage, when the building is decommissioned and is not intended to

Fig. 2 Organization of the life cycle inventory in accordance with the life cycle stages (Passer 2010)

	building life cycle		
life cycle stages	before use	use	end of life
impacts and aspects specific to building	building products construction process	use maintenance replacement refurbishment	de-construction/demolition recycling-potential disposal
impacts and aspects specific in operation		heating cooling ventilation lighting water consumption building integrated-technical systems	

have any further use. In the presented study, we assumed that the building would be dismantled/de-constructed at the end of its life stage and would provide a source of materials to be reused, recycled, recovered, or landfilled, depending on the type of construction product.

2.5 Quantification of the environmental performance

The calculation of the environmental performance is based on indicators according to FprEN15978. The underlying method is the LCIA according to ISO 14040. The indicators represent the quantifiable environmental impacts and aspects during the building life cycle. Environmental impacts are expressed with the impact category indicators of LCIA (e.g., global warming potential (GWP)) using characterization factors according to prEN 15804 (European Committee for Standardization 2010c), whereas environmental aspects are based on input flows of the LCI and describe, e.g., the use of renewable and non-renewable primary energy resources (cumulative energy demand (CED)). Out of the 22 indicators listed in the FprEN 15978,¹² seven environmental indicators were selected which are given in Table 5. These seven indicators have been chosen because they are commonly used in practice, e.g., also in building certification systems, and widely accepted calculation methods.

For the calculation of the indicators describing environmental impacts, the characterization methods for the impact assessment according to CML 2001¹³ (Guinée et al. 2001a,b) were chosen (see Table 5, “Indicators describing environmental impacts”). For calculation of the indicators describing resource use, the cumulative energy demand (see Table 5, “Indicators describing resource use”), which has been implemented in *ecoinvent* v2.1, was selected (Hischier et al. 2009).

¹² The environmental indicators proposed in the FprEN 15978 (FprEN15978) at the moment consist of seven indicators describing environmental impacts, eight indicators describing resource use, three indicators describing waste categories, and four indicators describing the output flows leaving the system.

¹³ CML, Centre of Environmental Science, Den Haag and Leiden, The Netherlands

The environmental indicator values for each indicator were calculated for each product in the different life cycle stages based on a matrix calculation routine (FprEN15978). This routine consists in multiplying each product and service quantified in the different life cycle stages of the building with its respective value for any environmental indicator. The same calculation routine was applied to all indicators listed in Table 5.

3 Results

We give first an overview of the environmental indicator results of the building life cycle for the five buildings, divided into construction products versus operation (Table 6). The detailed results are presented, mainly for the environmental indicators, split into the construction products caused by fabric and finishing, technical building equipment, and building operation (Table 7). Secondly, the environmental indicator results of the individual life cycle stages are shown in detail (Table 8). Finally, the influence of construction products used for technical building equipment is shown versus the fabric and finishing with its spread across the five buildings (Fig. 3).

3.1 Results for construction products and building operation

The percentage of construction products in relation to the building operation is shown in Table 6 over the building life cycle. It can be observed that building operation dominates the overall indicator results in all environmental categories whereas the ratio between construction products and operation may vary strongly (e.g., 48/52 % for building 1 to 62/38 % for building 4 on indicator AP).

The dominating factor influencing the ratio of the results is the requirement for electricity for household services, which, in low-energy buildings, is nearly equal to the final energy demand for heating and hot water (e.g., 56.2 vs. 53.4 kWh/m²a for 395 building 1, respectively; see Table 3). Household services were calculated according to the profiles in ÖNORM

Table 4 Classification of construction products according to the Austrian Standard ÖNORM B-1801-1

Building, fabric	Technical building equipment	Building, finishing
On-site overhead	Electrical installation	Plasterwork
Excavations	Heating	Floor screed work
Ground-water lowering work	Solar heating system	Roofer's work
Drainage work	Sanitary	Tinner's work
Sewer construction works	Ventilation	Tile fixing work
Concrete work		Joiner's work
Masonry work		Thermal insulation composite system
Proofing work		Coating (wood and metal)
Precast elements		Coating (masonry and plaster)
Winter construction work		Windows
Departmental construction work		Dry construction work
Ashlar masonry work		
Carpenter's work		

H 5055 (energy certificate), which incorporate several user profiles for residential buildings and matched with statistical values (Statistic Austria 2010). These values are a little higher than the values according to VDI 3807, but they are within the range of values published by Dodoo et al. (2011) (52 kWh/m²a final energy use for household and facility electricity).

Our results as regarding embodied and operational energy are in line with those reported by Optis and Wild (2010). Unfortunately, a detailed comparison of different LCA-case study results is not possible at the moment because of the inadequate documentation in published LCA on buildings, which is also pointed out by Optis and Wild (2010). Additionally, the quantification of the operational energy has to be reported in a transparent way (e.g., Dodoo et al. 2011).

Potable water consumption does not play a significant role in Austria within the assessment for the chosen impact categories.

3.2 Life cycle results

Table 7 shows the environmental indicator results for the five buildings per square meter net floor area per year for the

building life cycle; Table 8 gives the results for the environmental indicator during the individual life cycle stages: before-use, use, and end-of-life, respectively.

The variation of the results is mainly caused by the different energy performances and construction techniques in the assessed buildings. Nevertheless, the total spread including building fabric, finishing, technical building equipment and operation is rather small across buildings 2 to 5, all of them low-energy standard buildings. In contrast, a rather large range can be observed for several individual building components, e.g., the indicators for building 2 in the class fabric and finishing are lower compared with the ones of building 3 by almost a factor of 2. This is mainly caused by the fact that building 2 has light interior walls and a light roof construction, and it is the only one which uses timber-wood frame windows. Further differences result from different construction products installed in the assessed buildings, e.g., solid construction with the use of reinforced concrete and bricks vs. timber construction with the use of timber frame (see Tables 7 and 8). The largest difference can be attributed to construction products used for technical building equipment, e.g., ventilation system

Table 5 Indicators for characterizing environmental impacts and describing resource use

	Code	Unit
Indicators describing environmental impacts		
Acidification potential of land and water	AP	kg SO ₂ equiv
Eutrophication potential	EP	kg PO ₄ equiv
Global warming potential	GWP	kg CO ₂ equiv
Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 equiv
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg ethylene equiv
Indicators describing resource use		
Use of non-renewable primary energy (energy resources)	CEDnr	MJ-equiv
Use of renewable primary energy (energy resources)	CEDr	MJ-equiv

Table 6 Ratio of environmental indicators between construction products and operation over the building life cycle

	AP kg SO ₂ eq	EP kg PO ₄ eq	GWP kg CO ₂ eq	ODP kg CFC 11 eq	POCP kg ethylene eq	CEDr MJ-Eq	CEDnr MJ-Eq
Building 1							
Construction products	48 %	33 %	31 %	14 %	42 %	10 %	29 %
Operation	52 %	67 %	69 %	86 %	58 %	90 %	71 %
Building 2							
Construction products	49 %	44 %	19 %	8 %	36 %	40 %	18 %
Operation	51 %	56 %	81 %	92 %	64 %	60 %	82 %
Building 3							
Construction products	58 %	52 %	27 %	9 %	45 %	32 %	26 %
Operation	42 %	48 %	73 %	91 %	55 %	68 %	74 %
Building 4							
Construction products	62 %	57 %	33 %	13 %	54 %	18 %	30 %
Operation	38 %	43 %	67 %	87 %	46 %	82 %	70 %
Building 5							
Construction products	57 %	50 %	29 %	12 %	49 %	19 %	26 %
Operation	43 %	50 %	71 %	88 %	51 %	81 %	74 %

with air-to-air heat pump with heat recovery in building 1 versus conventional gas heating system combined with solar heating (e.g., 0.408E-02 vs 2.62E-02 kg PO₄ eq/m²a in building 1 and 4, respectively). These construction products are higher in efficiency than the heating systems installed in the low-energy buildings regarding their environmental indicator values over the building life cycle.

The project in the “passive-house” energy standard (building 1) has the least total environmental impact over the building life cycle. Furthermore, the passive house also shows a much lower fraction of the construction products used for the technical building equipment.

3.3 Results for the individual life cycle stages

In Table 8, the environmental indicators are itemized in the individual life cycle stages as well as in the different building performance classes (building fabric, technical building equipment, and finishing) for each assessed building.

3.4 Influence of the technical building equipment

Finally, the influence of construction products used for technical building equipment is illustrated in relation to the fabric and finishing. Figure 3 specifies the range within the five assessed buildings over the building life cycle for all environmental indicators selected.

The influence of the installed technical building equipment is remarkable, as can be inferred from the indicator values in the before-use stage which can be found across a broad range as well over the building life cycle. The

magnitude of indicator results suggests that the level of environmental significance associated with construction products used for technical building equipment should not be excluded from any study when specifying the cut-off criteria.

The most important contribution to the environmental indicators results stemming from technical building equipment is in the impact categories eutrophication potential (EP), acidification potential (AP), and formation potential of tropospheric ozone photochemical oxidants (POCP) (see Fig. 3a, b and e, respectively).

The high environmental indicator results for EP and AP, 12 % to 43 % and 10 % to 24 %, respectively, are mainly due to construction products used for the technical building equipment, e.g., the heating systems, electrical installations, and solar heating systems. The high value derives from metals, especially from copper products resulting from the use of primary copper, as also mentioned by, e.g., Prek 2004. It has been noticed that, for those products, the trend of the indicator EP correlates predominantly with the indicator AP. In contrast to that, the impacts in the category POCP are influenced additionally by other construction products, mainly plastic materials. Regarding the impact categories GWP and ODP as well as the environmental aspects CEDr and CEDnr, construction products used for the technical building equipment are of low importance (less than 5 %).

While the use of a combined solar heating system for providing hot water reduces the impacts in the in-use stage, it amplifies the impacts in the before-use stage. Replacement rates for the technical building equipment decide if and to which

Table 7 Environmental indicator results over the building life cycle

	Building life cycle						
	AP kg SO2 eq	EP kg PO4 eq	GWP kg CO2 eq	ODP kg CFC 11 eq	POCP kg ethylene eq	CEDr MJ-Eq	CEDnr MJ-Eq
	(environmental indicators/m² NFA*a]						
Building 1							
Fabric and finishing	4,40E-02	7,29E-03	1,42E+01	9,93E-07	2,45E-03	2,90E+01	1,83E+02
Technical equipment	1,10E-02	4,08E-03	1,50E+00	1,09E-07	4,62E-04	2,29E+00	2,30E+01
Operation	5,87E-02	2,29E-02	3,56E+01	6,96E-06	4,07E-03	2,92E+02	5,16E+02
Total	1,14E-01	3,43E-02	5,12E+01	8,07E-06	6,98E-03	3,23E+02	7,22E+02
Building 2							
Fabric and finishing	3,73E-02	6,17E-03	9,25E+00	8,07E-07	2,07E-03	1,16E+02	1,33E+02
Technical equipment	2,35E-02	1,70E-02	2,53E+00	1,42E-07	1,03E-03	2,78E+00	4,07E+01
Operation	6,41E-02	2,92E-02	5,08E+01	1,10E-05	5,61E-03	1,80E+02	8,06E+02
Total	1,25E-01	5,24E-02	6,26E+01	1,20E-05	8,71E-03	2,99E+02	9,79E+02
Building 3							
Fabric and finishing	5,32E-02	8,61E-03	1,38E+01	8,22E-07	2,86E-03	7,20E+01	2,08E+02
Technical equipment	2,79E-02	2,14E-02	2,80E+00	1,61E-07	1,22E-03	3,17E+00	4,51E+01
Operation	5,75E-02	2,75E-02	4,56E+01	9,91E-06	5,04E-03	1,59E+02	7,23E+02
Total	1,39E-01	5,75E-02	6,22E+01	1,09E-05	9,12E-03	2,34E+02	9,76E+02
Building 4							
Fabric and finishing	5,21E-02	8,83E-03	1,63E+01	1,01E-06	3,72E-03	3,03E+01	2,17E+02
Technical equipment	3,39E-02	2,62E-02	3,34E+00	2,97E-07	1,52E-03	3,94E+00	5,41E+01
Operation	5,25E-02	2,65E-02	3,99E+01	8,56E-06	4,44E-03	1,61E+02	6,26E+02
Total	1,39E-01	6,15E-02	5,95E+01	9,86E-06	9,68E-03	1,95E+02	8,97E+02
Building 5							
Fabric and finishing	5,17E-02	8,73E-03	1,64E+01	1,02E-06	3,58E-03	3,81E+01	2,18E+02
Technical equipment	2,65E-02	2,07E-02	2,59E+00	2,87E-07	1,22E-03	3,16E+00	4,21E+01
Operation	5,93E-02	2,91E-02	4,59E+01	9,92E-06	5,09E-03	1,74E+02	7,25E+02
Total	1,38E-01	5,85E-02	6,50E+01	1,12E-05	9,90E-03	2,15E+02	9,85E+02

extent benefits regarding environmental impacts can be gained over the building life cycle.

4 Discussion

The paper has attempted to present the influence of the technical building equipment on residential buildings by concluding a wide set of environmental performance indicators. This is essential due to the fact that components of the technical building equipment have different influence on the selected single environmental performance indicators.

From the authors' point of view, not taking into account the technical building equipment is one of the major deficiencies of simplified LCAs. Thus, for example, in undertaking simplified LCA, the following issues are not considered: first of all, all construction works, e.g., building

fabric, technical building equipment, and finishing; secondly, the constructive design, e.g., cornering, connections, and clipping. The latter also includes the definition of the cut-off rules, e.g., based on mass-percentage, and the selection of the functional unit, e.g., square meter gross floor area versus net floor area. We suggest to use the square meter NFA as functional unit for building LCA, which is not usual for energy certification (at least in Austria), but, in terms of LCA of buildings, this functional unit seems more appropriate. Otherwise, buildings with high (i.e., thick) thermal insulation would benefit more than average, as their ratio between net and gross floor area is always the lowest.

Another major point is the selection of the environmental indicators. The results also point out that a broader number of indicators should be used because several materials, i.e., metals, have a strong influence on only some indicators, e.g., EP. Solely taking, e.g., CED or GWP into

Table 8 Environmental indicator results for the individual life cycle stages

	Before use							Use		
	[environmental indicators/m² NFA*a]							[environmental indicators/m² NFA*a]		
	AP kg SO2 eq	EP kg PO4 eq	GWP kg CO2 eq	ODP kg CFC 11 eq	POCP kg ethylene eq	CEDr MJ-Eq	CEDnr MJ-Eq	AP kg SO2 eq	EP kg PO4 eq	GWP kg CO2 eq
[environmental indicators/m² NFA*a]										
Object 1 Fabric and finishing Technical equipment Operation Total	2.84E-02	4.52E-03	9.98E+00	6.51E-07	1.66E-03	2.50E+01	Object 1 1.21E+02	8.89E-03	1.35E-03	2.29E+00
	5.94E-03	2.13E-03	6.41E-01	5.56E-08	2.35E-04	1.08E+00	1.23E+01	4.99E-03	1.94E-03	7.06E-01
	3.43E-02	6.65E-03	1.06E+01	7.07E-07	1.90E-03	2.61E+01	1.33E+02	5.87E-02	2.29E-02	3.56E+01
	2.65E-02	4.07E-03	6.93E+00	5.65E-07	1.59E-03	1.02E+02	Object 2 9.89E+01	7.26E-02	2.62E-02	3.86E+01
Object 2 Fabric and finishing Technical equipment Operation Total	8.77E-03	6.73E-03	7.21E-01	4.98E-08	3.82E-04	9.81E-01	1.42E+01	1.47E-02	1.03E-02	1.63E+00
	3.52E-02	1.08E-02	7.65E+00	6.15E-07	1.97E-03	1.03E+02	1.13E+02	6.41E-02	2.92E-02	5.08E+01
	3.17E-02	4.89E-03	7.95E+00	4.74E-07	1.84E-03	6.62E+01	Object 3 1.30E+02	8.43E-02	4.03E-02	5.36E+01
	9.13E-03	7.09E-03	7.39E-01	5.13E-08	3.97E-04	1.01E+00	1.45E+01	1.57E-02	2.50E-03	3.61E+00
Object 3 Fabric and finishing Technical equipment Operation Total	4.08E-02	1.20E-02	8.69E+00	5.26E-07	2.23E-03	6.72E+01	1.44E+02	1.87E-02	1.43E-02	1.88E+00
	2.99E-02	4.91E-03	9.66E+00	5.98E-07	2.36E-03	2.47E+01	Object 4 1.28E+02	5.75E-02	2.75E-02	4.56E+01
	1.11E-02	8.67E-03	9.02E-01	9.63E-08	4.99E-04	1.27E+00	1.75E+01	9.19E-02	4.43E-02	5.11E+01
	4.10E-02	1.36E-02	1.06E+01	6.95E-07	2.86E-03	2.60E+01	1.46E+02	1.57E-02	2.58E-03	4.15E+00
Object 4 Fabric and finishing Technical equipment Operation Total	3.15E-02	5.09E-03	1.03E+01	6.50E-07	2.40E-03	3.25E+01	Object 5 1.40E+02	2.26E-02	1.75E-02	2.24E+00
	1.18E-02	9.17E-03	9.53E-01	1.11E-07	5.31E-04	1.35E+00	1.84E+01	5.25E-02	2.65E-02	3.99E+01
	4.33E-02	1.43E-02	1.13E+01	7.61E-07	2.93E-03	3.39E+01	1.58E+02	9.09E-02	4.66E-02	4.63E+01
								1.35E-02	2.24E-03	3.52E+00
Object 5 Fabric and finishing Technical equipment Operation Total								1.47E-02	1.14E-02	1.43E+00
								5.93E-02	2.91E-02	4.59E+01
								8.75E-02	4.28E-02	5.09E+01

Table 8 (continued)

Use		End of life									
[environmental indicators/m ² NFA*a]				[environmental indicators/m ² NFA*a]							
ODP kg CFC 11 eq [environmental indicators/m ² NFA*a]	POCP kg ethylene eq	CEDr MJ-Eq	CEDnr MJ-Eq	AP kg SO2 eq [environmental indicators/m ² NFA*a]	EP kg PO4 eq	GWP kg CO2 eq	ODP kg CFC 11 eq	POCP kg ethylene eq	CEDr MJ-Eq	CEDnr MJ-Eq	
Object 1											
1.60E-07	5.72E-04	3.69E+00	4.07E+01	6.75E-03	1.43E-03	1.88E+00	1.82E-07	2.19E-04	2.95E-01	2.18E+01	
5.26E-08	2.26E-04	1.20E+00	1.05E+01	4.74E-05	8.72E-06	1.58E-01	7.59E-10	1.95E-06	8.10E-03	1.44E-01	
6.96E-06	4.07E-03	2.92E+02	5.16E+02	6.79E-03	1.44E-03	2.04E+00	1.83E-07	2.21E-04	3.03E-01	2.19E+01	
7.18E-06	4.87E-03	2.97E+02	5.67E+02	Object 2							
1.13E-07	3.32E-04	1.36E+01	1.92E+01	5.19E-03	1.24E-03	1.13E+00	1.29E-07	1.48E-04	1.24E-01	1.46E+01	
9.11E-08	6.43E-04	1.78E+00	2.63E+01	9.12E-05	1.60E-05	1.78E-01	1.44E-09	3.74E-06	1.78E-02	2.94E-01	
1.10E-05	5.61E-03	1.80E+02	8.06E+02	Object 3							
1.12E-05	6.59E-03	1.96E+02	8.51E+02	5.28E-03	1.26E-03	1.31E+00	1.31E-07	1.51E-04	1.41E-01	1.49E+01	
2.19E-07	8.34E-04	5.24E+00	6.05E+01	5.82E-03	1.23E-03	2.28E+00	1.29E-07	1.91E-04	5.25E-01	1.79E+01	
1.08E-07	8.17E-04	2.14E+00	3.03E+01	9.19E-05	1.62E-05	1.83E-01	1.45E-09	3.77E-06	1.79E-02	2.95E-01	
9.91E-06	5.04E-03	1.59E+02	7.23E+02	Object 4							
1.02E-05	6.69E-03	1.67E+02	8.14E+02	5.91E-03	1.24E-03	2.46E+00	1.31E-07	1.95E-04	5.43E-01	1.81E+01	
2.42E-07	1.14E-03	5.09E+00	6.79E+01	6.53E-03	1.35E-03	2.52E+00	1.65E-07	2.19E-04	4.38E-01	2.11E+01	
1.99E-07	1.02E-03	2.65E+00	3.63E+01	9.67E-05	4.98E-05	1.99E-01	1.58E-09	4.31E-06	2.15E-02	3.27E-01	
8.56E-06	4.44E-03	1.61E+02	6.26E+02	Object 5							
9.00E-06	6.59E-03	1.68E+02	7.30E+02	6.63E-03	1.40E-03	2.72E+00	1.66E-07	2.23E-04	4.60E-01	2.14E+01	
1.98E-07	9.61E-04	5.16E+00	5.76E+01	6.66E-03	1.41E-03	2.57E+00	1.67E-07	2.18E-04	4.11E-01	2.11E+01	
1.75E-07	6.84E-04	1.79E+00	2.33E+01	9.82E-05	6.05E-05	2.04E-01	1.62E-09	4.48E-06	2.26E-02	3.37E-01	
9.92E-06	5.09E-03	1.74E+02	7.25E+02	Object 6							
1.03E-05	6.74E-03	1.81E+02	8.06E+02	6.76E-03	1.47E-03	2.77E+00	1.69E-07	2.23E-04	4.34E-01	2.14E+01	

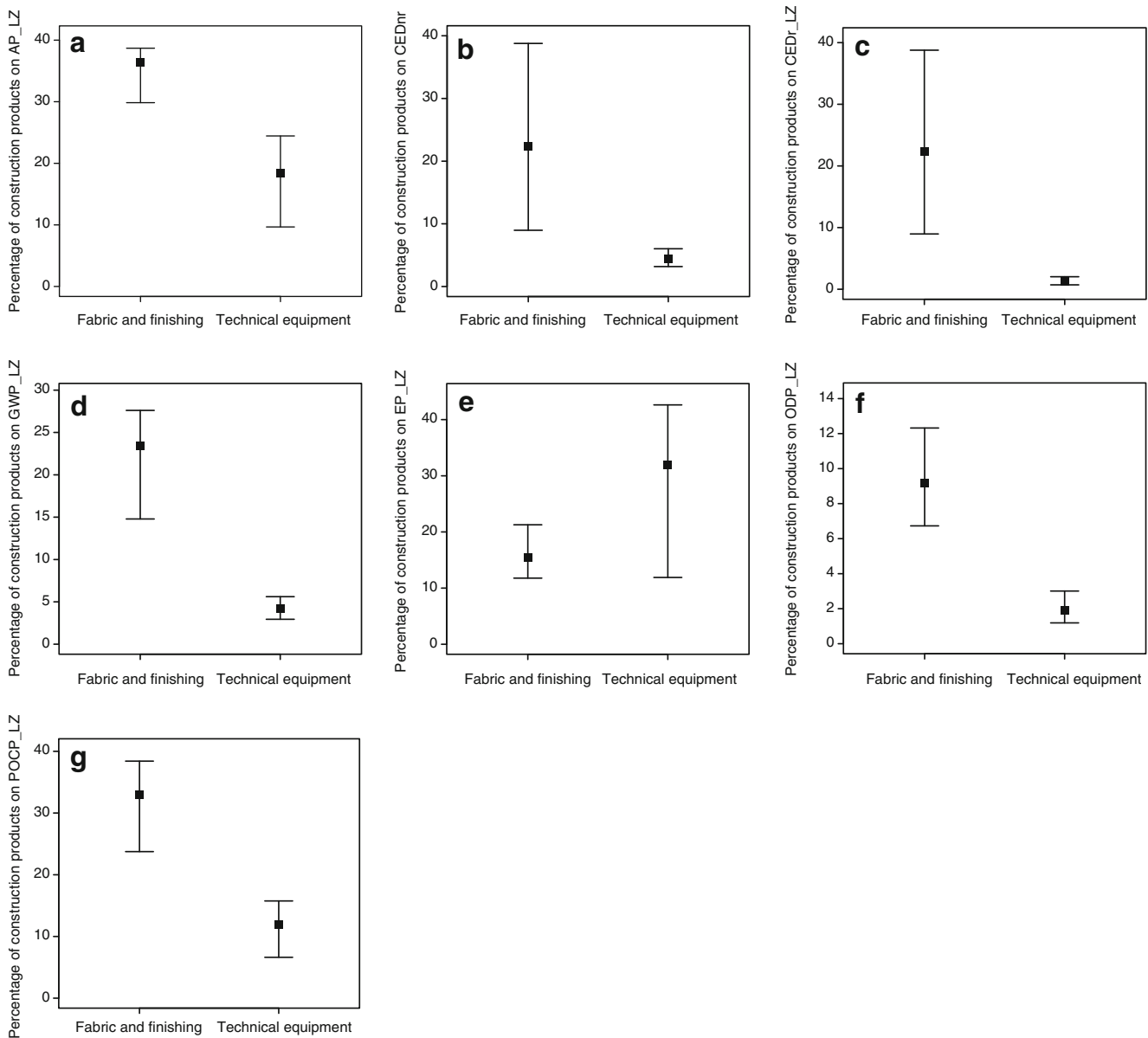


Fig. 3 Influence on selected indicators over the building life cycle of fabric and finishing and technical building equipment, respectively (**a** AP_LZ, **b** CEDnr_LZ, **c** CEDr_LZ, **d** GWP_LZ, **e** EP_LZ, **f** ODP_LZ,

g POCP_LZ). *Black square* shows average values, *whiskers* indicate minimum and maximum values ($n=5$ objects)

account would definitely draw a wrong environmental performance profile. Although there is still a lack of agreed indicators for, e.g., resource use, land use, or human and ecotoxicity, a broader number on environmental indicator is currently also proposed by the upcoming European standards (FprEN15978).

The results of the case study showed the importance of the role of the technical building equipment in LCA and how it contributes to the overall building performance, which is shown in Fig. 3 for the selected environmental indicators. Due to the important role of LCA in the criteria weighting in several building certification systems, a

detailed consideration of the technical building equipment is therefore indispensable. However, several certification systems still ignore the assessment of the technical building equipment. From the authors' point of view, this is caused by the fact that currently there is a great lack of data for the technical building equipment and its required products/components. With the current growing number of EPDs (EN 15804), it is assumed that the lack of data will get less important, more and more in near future.

The overall high influence of the operational energy versus the construction products in the results as regards the environmental performance underlines how important it

is to focus on optimizing the operational energy performance in general. Due to the fact that the optimization of the energy performance has already reached a high level in Austria, the remaining optimization potential that may still be raised might be low, especially in low-energy and passive-house standard residential buildings.

In the case studies selected by the authors, this is caused in particular by the fact that the requirement for electricity for household services is nearly equal to the final energy demand for providing heating and hot water in low-energy buildings. Due to this reason, new approaches need to be integrated into building certification systems for household devices, e.g., Ciriterion from Minergie (Minergie 2011).

Moreover, the LCA findings have identified a high optimization potential for the construction products used for the technical building equipment as well as for the building fabric and finishing. This has been demonstrated by assessing different residential buildings built by using different construction techniques. Analyzing the environmental indicator values in the before-use stage, the results do not indicate any clear trends in the building performance class “fabric” and “finishing.” For the energy standards, this means that these absolute values are influenced more strongly by different surface-to-volume ratios than by different construction techniques, although the buildings in timber construction show lower environmental indicator values than the buildings built in solid construction technique. So, optimization for environmental indicators should, first of all, be focused on optimizing the surface-to-volume ratios, then on optimizing the energy standard by the choice of the thermal insulation and technical building equipment and, finally, on the construction products for fabric and finishing. Concluding in terms of LCA a combination of the mentioned construction methods and technical building equipment would lead to the best LCA performance.

Regarding the CPR the end-of-life/deconstruction phase will gain more importance in the near future. So it is expected that more detailed datasets for the end-of-life phase will be available in the future which can allow a more detailed assessment. However, from the Authors point, the assessment of dismantling/deconstruction and recycling technologies for the end-of-life phase is hardly predictable from today’s perspective. In this context, the focus should rather be on an investigation and assessment of dismantling ability of the construction for the end-of-life phase.

The quantification of the environmental performance of building requires the utilization of assessment tools, which have been developed in the last two decades in a significant number. These tools have already been critically evaluated by researchers and practitioners. Until now, the assessment of the technical building equipment is often still neglected in building LCA.

In order to achieve more sustainability in the construction sector appropriate tools for the assessment

environmental performance of buildings are needed which generate simultaneously the appropriate data. These tools could form the basis for key decisions in early planning phases.

5 Conclusions

Sustainability assessments of buildings using the life cycle approach have become more and more common. This includes the assessment of the environmental performance of buildings. However, the influence of the construction products used for the fabric, the finishing, and the technical building equipment of buildings has hardly been described in literature. In contrast, in this study, five residential buildings were evaluated by applying the methodology of life cycle assessment (LCA acc. to ISO14040) expressed using quantitative assessment categories according to FprEN15978.

Results show that the optimization of energy performance has already reached a high level in Austria, so that the overall potential for possible improvements is quite low. Especially in low-energy and passive-house-standard residential buildings, the limits for energy optimization in the use phase have mostly been achieved. In contrast to this, the iLCA findings attribute a high optimization potential to the construction products used for the technical building equipment as well as to the building fabric and finishing. Additionally, the passive house shows the lowest contribution of the technical building equipment on the overall LCA results, which is mainly caused by the lack of “conventional” technical building equipment for heating.

As certification systems for buildings can play a key role in transforming the market towards more green and sustainable buildings, it should be assured that these systems implement complete LCA methods. This need is clearly emphasized by the results presented in this work.

To conclude, on the basis of the iLCA findings, it is strongly recommended that the building component class of the technical building equipment should be included in the assessment of the environmental performance of buildings.

Acknowledgments We acknowledge the suggestions of two anonymous reviewers who helped to improve this manuscript.

The analysis and results described in this paper are part of the PhD research of A. Passer at Graz University of Technology, supervised by P. Maydl and H. Wallbaum.

The authors would like to thank C. Mitterer for providing help with data illustration.

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